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PERT for the engineer

Engineers may associate PERT with large military programs and computers, but they should know that PERT can also be applied effectively to modest engineering tasks

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Although PERT (Program Evaluation and Review Technique) was successfully introduced in 1958 on the Polaris Weapons System Program and subsequently it and similar networking techniques were enthusiastically accepted in the management of the development phase of weapons systems programs, as well as within industries such as construction, we now observe a curious phenomenon. Many engineers, employed as project engineers either by large corporations on major programs or by small laboratories engaged in component or subsystem development, still question the effectiveness of PERT for their own use. Much of the cynicism that greets the technique can be traced, in part, to a lack of conviction on the part of engineers that PERT can be an effective planning and control technique for modest task applications as well as for large programs necessitating elaborate, computer-based applications.

When should PERT be used?

This article is directed at the individual engineer or project engineer engaged in an engineering task or small project, whether oriented toward defense or commercial products. The size of the task does not affect the requirement for planning nor need it influence the decision to use PERT techniques. PERT techniques for planning and control, involving graphic methods and network analysis to depict and analyze a project, can be applied to large or small projects, formally or informally. The nature of the project does, however, influence this decision. The networking technique is applicable primarily to the "once-through" type of effort typically associated with the development of a system or subsystem, that is, one where

- The objective of the effort is to realize an engineering model or prototype model of a hitherto nonexistent item or items of equipment.
- The achievement of the objective involves some degree of uncertainty because of the lack of directly applicable experience on which to base estimates.
- The achievement of the objective is subject to significant changes in direction, intensity, and scope as the work progresses.

Efforts of a repetitive nature and predictable course, such as volume production runs, are normally better planned and managed through the use of other techniques (for example, Line-of-Balance). There is, however, no clear cutoff point between the once-through process and the repetitive process when development programs include the production of initial or limited quantities of end items.

Basic research programs and endeavors aimed at breakthroughs in the state-of-the-art are less amenable to PERT even though they, too, are normally once-through processes. *PERT becomes less meaningful when objectives cannot be clearly defined.*

Within these limits, networking may be successfully applied. This does not imply that PERT and other networking techniques such as CPM (Critical Path Method) apply only to developmental engineering tasks. The applications are as varied as industry itself. These techniques have been applied and found useful in the following areas:

Government research and development
Commercial product development
Installation of equipment
Construction
First production runs
Maintenance
Systems and procedures installation
Training programs
Movie and stage productions

Military electronics, at one time the predominant user of PERT techniques, can no longer make this claim. Booz, Allen and Hamilton, Management Consultants, reported that, "By 1963, 85 per cent of the companies surveyed were using PERT either exclusively or partially for private commercial work."[1] Although diverse applications have bred many variations of the techniques, the basic concepts have not changed.

What PERT is and is not

Before PERT methods of planning and control are discussed, several myths shrouding these techniques must be dispelled. Conventional, nonprobabilistic, bar chart planning led to the popular belief, reinforced by many engineers, that research and development work cannot aptly be measured in terms of time and cost progress. "You can't schedule invention," "You can't expect us to design by the calendar," "Mental processes can't be planned" are frequent statements heard. PERT, with a probabilistic approach to time planning, has helped to dispel this myth.

Whenever a new technique such as PERT is developed, it tends to introduce a new breed of specialist, and a new language is promulgated which is understood, presumably, only by the "privileged few." When discussing their work, PERT specialists ("PERTniks") use terms such as slack, critical path, expected time, latest allowable time, and a host of others. Because PERT specialists in staff and line positions are needed for large-scale PERT applications, some people are led to believe that PERT is a mystical system, complicated to use and one which will not prove durable. In practice, however, PERT is surviving, and the techniques do not necessarily require specialist personnel for intelligent application. It has been suggested by some writers[2] that a PERT analysis staff be eliminated and that project engineers perform this function. The suggestion has merit and certainly is correct in its implication that the engineer or project engineer plays a key role in a successful PERT system.

The reason that PERT applications continue to expand is that the technique provides many advantages. Among these are

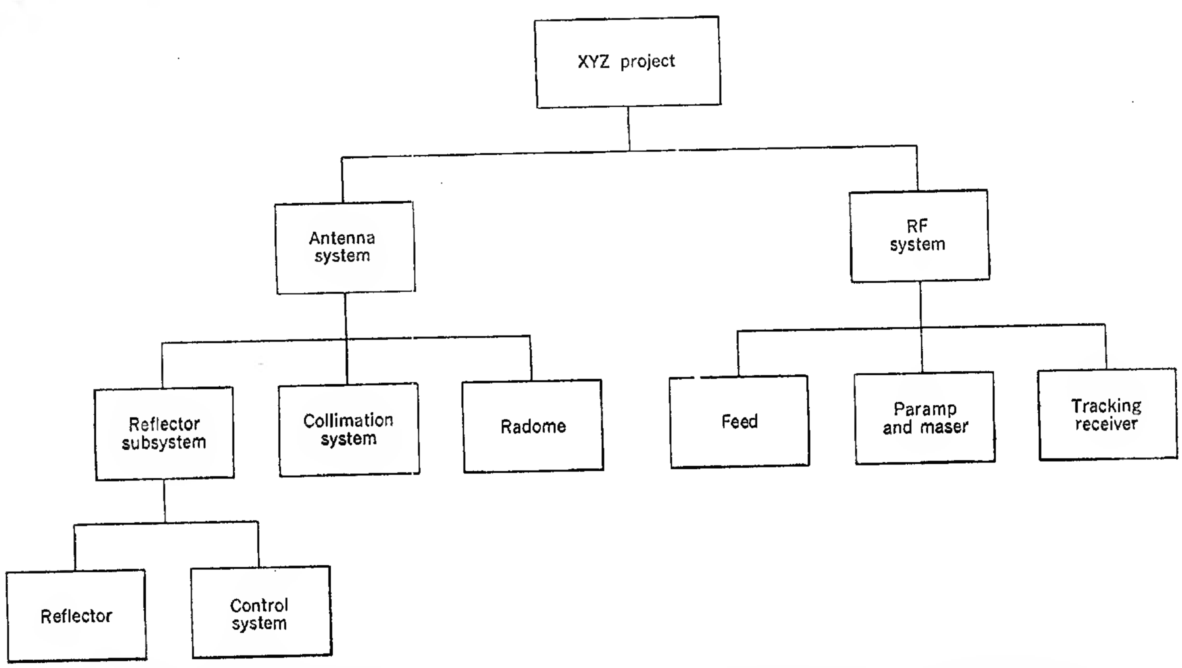
- A disciplined approach to planning.
- A method of visualizing the work and of communicating plans.
- A plan which can reflect uncertainties but which can also be easily used for calculating the time to perform the project.
- A means for appraising progress and forecasting problem areas.

The subsequent sections define the steps that should be followed in planning a project, large or small, and the networking techniques that should be applied. Many of these techniques are not unique to networking but have been in use for a long time. This is why we refer to PERT as being both evolutionary and revolutionary.

Before delving into the how and why of PERT, let us define what it is. PERT is a planning and control discipline which employs a specific set of principles, methods, and techniques for effective planning. The key elements of this discipline are

- A *work breakdown structure*, which begins with the objectives and subdivides them into successively smaller elements of work.
- A *network*, comprising all the work which must be accomplished to reach the objectives, and depicting the planned sequence of accomplishment of this work as well as the interdependencies and interrelationships.
- Elapsed time *estimates* of work to be performed and *schedules* which also consider the availability of resources.

Fig. 1. Typical engineering equipment breakdown or "family tree."



- *Analysis* of the interrelated networks and schedules as a basis for continued evaluation of performance and identification of problem areas.

PERT is also a discipline for organizing data, documenting the plan, and manipulating the plan to effect a successful conclusion to the project. The statement that PERT is a discipline and a tool for planning and controlling a job is significant to an understanding of the technique. Although the technique is formalized it is no different from what any of us must ordinarily do to plan and control our work properly. As will be seen, elements of this technique had their origin in engineering applications. It must be remembered that PERT is not a panacea or substitute for the decision-making process; it is only a tool to aid the decision makers.

Defining the job

Before any project or task, large or small, can be undertaken it must be defined. The engineer must define the objectives in terms such as final hardware. The hardware, perhaps, can be broken down into various levels such as assemblies, subassemblies, and components. This exercise is generally expressed on paper by the preparation of a "family tree" or "Christmas tree" equipment breakdown. This breakdown, dividing the piece or pieces successively into component parts (see Fig. 1), is the "road map" for the designer or project engineer. In any project there may be other end-item requirements such as engineering data and ancillary items. It is possible and practical to expand the family tree to include these items. The expanded family tree that evolves is known in the language of PERT as a *work breakdown structure*. The work breakdown structure does not stop at the level of end-item hardware, data, and services. As can be seen in Fig. 2, the breakdown continues to a definition of the required tasks such as design, fabrication, and test of each piece of hardware.

The resultant work tasks or *work packages* are likely to be assigned as separate responsibilities to organizations or individuals and are thus defined separately. As the family tree provided a road map for designing, so the work breakdown structure provides a road map for planning. The work breakdown structure establishes the basis for

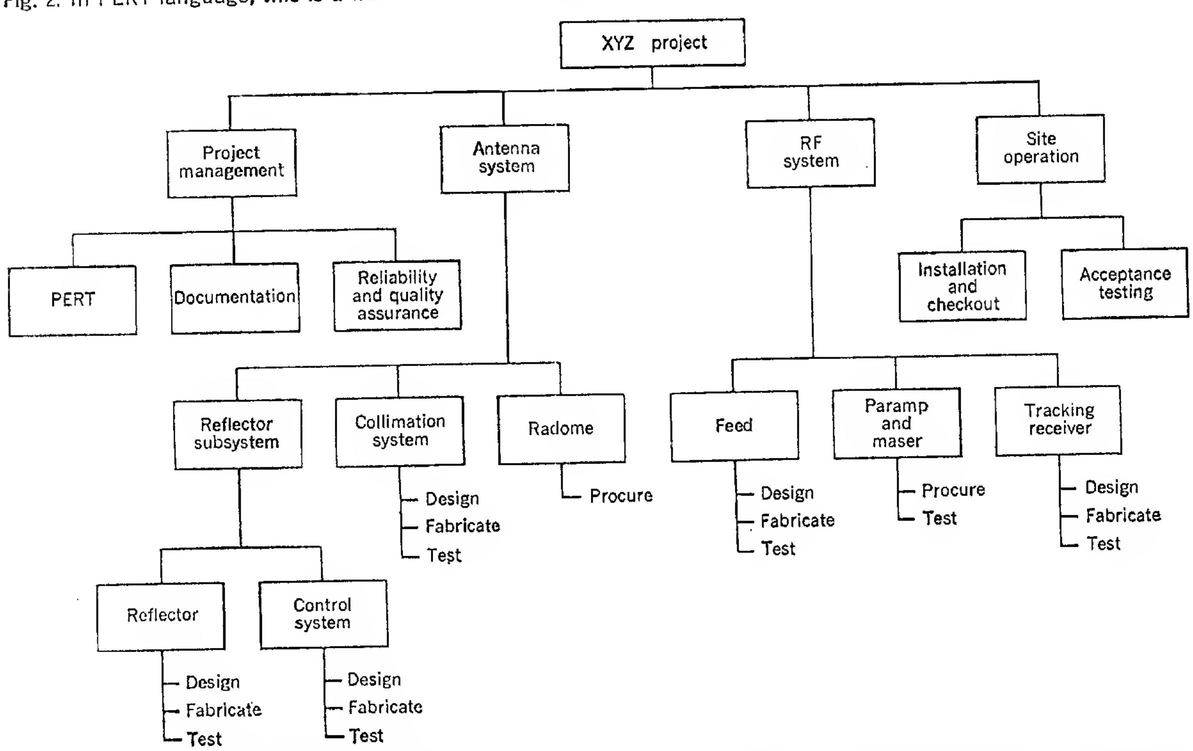
- Defining and relating the work to be performed and the program objectives.
- Identifying the responsibility for accomplishment of the work packages and monitoring at higher levels.
- Detailed PERT planning and control.
- Cost planning and control.

In a project, the work packages must be defined in detail. This is usually done either by simple written descriptions on a small project, or on a larger, complex program by more formal task authorizations. These should define the specifications, performance parameters, and the budget and schedule for the work packages. While these define the work in terms the engineer can understand, the plan for performance of this work remains to be prepared.

Network planning

Network planning or PERT was developed primarily to fill the need for a tool that would allow the engineer to depict what really was going to happen in his relatively

Fig. 2. In PERT language, this is a work breakdown structure.



complex R&D task or project. The Gantt or milestone charts which were in use for planning had been adapted from production planning methods and were found wanting. Networking techniques were derived from those used in electrical engineering and from flow charting used in computer programming. Networking is a logical discipline for planning a task. It is not the *network* which is prepared; it is the *plan* which is prepared using *network discipline*. This distinction is basic for an appreciation of networking as a planning and control tool for the engineer.

The discipline of planning can be defined by a series of questions which must be answered:

- What work must be performed?
- What is needed to perform this work?
- How will completion be identified?

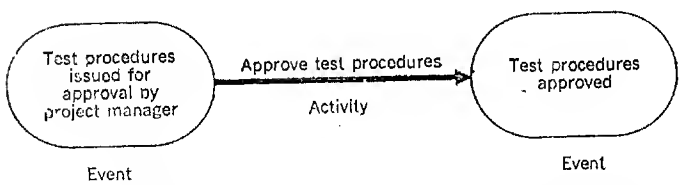
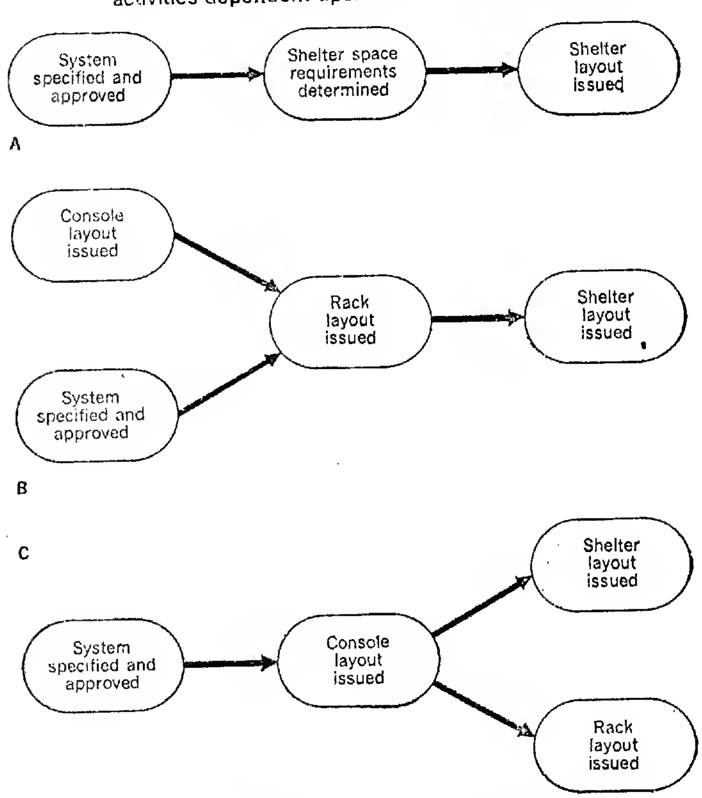


Fig. 3. Basic elements of a PERT network are events and activities.

Fig. 4. Network relationships: serial activities (A), an activity dependent upon parallel activities (B), and parallel activities dependent upon one restraining activity (C).



These questions can only be answered accurately by the responsible engineer or project engineer. When he thinks of his task in terms of these questions, he can plan in detail using a network approach. Once he has delineated the work and its sequence in detail, he may consider another very important question:

- How long will it take to perform the work?

The basic advantage of planning by this discipline is that it requires the engineer to think of his work in its entirety and to consider all of the individual parts.

Simply, a PERT network or chart is made up of two elements: events and activities. Activities are the work to be performed and are signified by arrows. Events are specific definable achievements—either the beginning or completion of one or more activities—and are represented on the network by circles, ellipses, rectangles, or other geometric figures. Every activity is bounded by an event at the beginning and an event at the end (see Fig. 3).

The method of preparing a network simply involves connecting activities and events to show their relationship. If one activity cannot be performed until another has been completed, it should be drawn as shown in Fig. 4(A). If, on the other hand, the activity cannot start until more than one activity is complete, it should be drawn as in Fig. 4(B).

Another type of network interrelationship exists in which more than one activity may start when a single previous activity has been completed. This type of constraint and parallel start is shown in Fig. 4(C). It is important to remember that the network represents logical restraints, *not* time sequencing. The network shows which activities *must* be accomplished before another may start. It should not be drawn to show all activities that may, because of preconceived ideas, be occurring prior to another in time only. If the activity can be performed regardless of the status of other activities, no constraint should be shown. Figure 5 shows an example of an abbreviated network.

Once the above principles of networking are understood, many other questions regarding rules of preparation are raised. One of the first is: How do we prepare it—do we start at the beginning and work toward the end or do we start at the end and work toward the beginning—what is the "standard" method? Although some articles in the past have extolled the virtues of one or the other method, we have found that *there is no "standard" method*. One can start at the front, back, or even in the middle, in preparing a network; it depends on the individual or group planning the job. If, as is frequently possible, a more effective plan can be developed by working from the end towards the beginning, then the network should be drawn accordingly. If you prefer, start at the beginning; once the network is prepared, however, it must represent the complete plan for accomplishing the job.

Another frequently asked question is: How large is a good network? A quick answer might be: Large enough to be a complete plan of the work to be performed. This answer only provokes another request for some guidelines for measurement. We have seen networks with thousands of activities (on a major weapons systems program) and with as few as 20 to 25 (on a small task). These were both good for their uses. Conversely, very small networks have been developed for very large projects and some

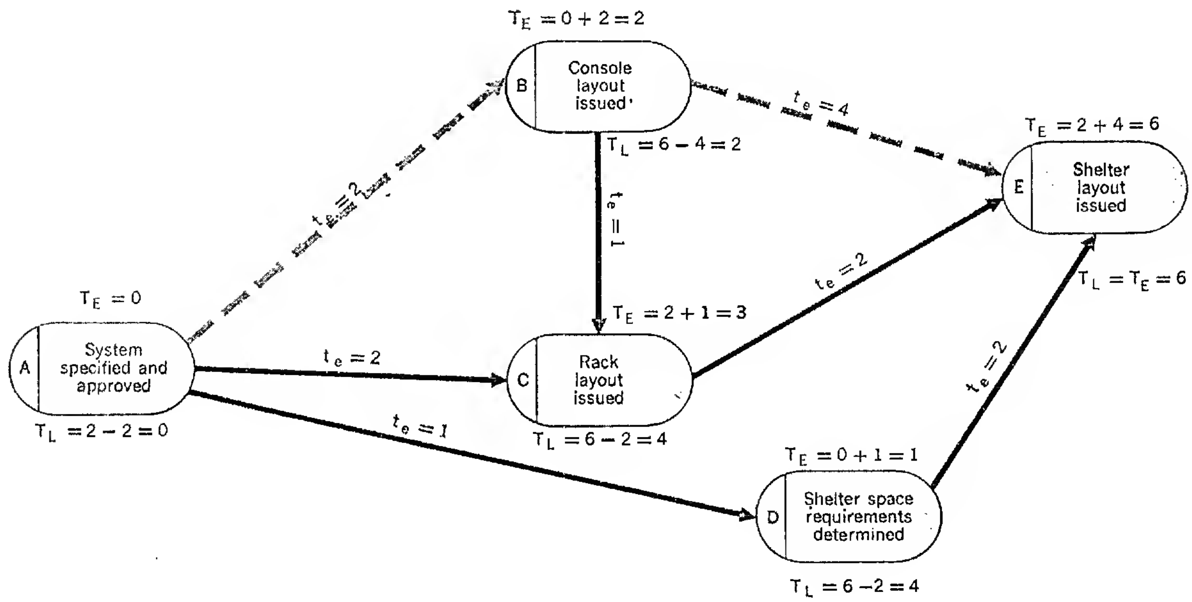


Fig. 5. Example of a PERT network structure, where t_e is statistically expected time of activity, T_E is earliest expected date, T_L is latest allowable date, and dashed line is critical path.

very large networks developed for small projects, none of which constituted a good plan. The basic problem with these networks was that preconceived artificial limits were set on network size. Such limits—"no fewer than 150 activities," "no greater than 100 activities," "on a sheet of paper no larger than one foot by two feet"—are usually artificial and should be avoided whenever possible. The first rule is to prepare the network without regard for size or neatness and then, when it is complete, worry about the size limitations that may be imposed. As a rule of thumb, with full regard to the differences in projects in their scope, technical sophistication, and duration, we have found that there should be an average elapsed time for the majority of the activities approximately equal to the period between progress reviews. As an example, if the network is reviewed weekly (as might be the case in a small engineering job), the activities should average 1–1½ weeks. If the network is reviewed monthly, the average should be 3–4 weeks. Although this is not a hard and fast rule, we have found it to hold true in most cases. This may seem to contradict our comment that the network should be prepared first and the duration estimated second, but network size is not really checked until time estimating is completed. This procedure is not illogical for it has been found that many networks undergo major modifications and improvements as time estimates are made.

Definitions

Optimistic time (a) = The time the activity will take if everything to be done is done successfully the first time.

Most likely time (m) = The time required to accomplish an activity under normal circumstances with some success and some failure.

Pessimistic time (b) = The time the activity will take with extremely bad luck.

Time estimating

Once the network has been developed, portraying the relationships and interdependencies among the activities, the time needed for each activity should be estimated. This should be done by the engineers who are going to do the work.

There are two basic methods of time estimating, probabilistic and deterministic, and the use of one or the other is optional.

Probabilistic time estimating, which was developed as part of the PERT system, requires three estimates for the duration of an activity (see Definitions). These three estimates are plotted on a beta distribution to find statistically expected time $t_e = (a + 4m + b)/6$, where t_e is expected time, a is optimistic time, m is most likely time and b is pessimistic time. (For a detailed discussion of these formulas, see Ref. 3.) This expected time, the weighted mean, is then used in all PERT calculations; it represents a probability of 50 per cent. A distinct advantage of this system is that the engineer is able to express his uncertainty in terms of these three estimates rather than having to express a more certain single time estimate. The three estimates also provide a means of assessing the risk being taken in performing the job. The three-time-estimate system is specifically designed for uncertain, nonrepetitive types of work.

Deterministic, or single time estimating, on the other hand, does not utilize probability weighting. The engineer can make one estimate for the length of the activity which is the time he needs to accomplish it. The single time estimate has been used mainly in process industries and construction where it has been found valuable. CPM, which is a networking system employing a slight vari-

ation of PERT in terms and method of network preparation, also uses one time estimate.

Once the time for the activities has been estimated and in the case of the three-time-estimate system, the expected time for the activity calculated, the expected length of the project can be calculated. Also, the expected dates for each event can be determined. The expected length of the project (the sum of the t_e's on the longest network path) is referred to as the earliest expected date (T_E). It is calculated by summing the expected times of the activities from the start through the completion of each network path (see Fig. 5). Once the T_E is calculated, the T_L, or latest allowable date, is calculated by starting with a predetermined date for the end event and subtracting the expected elapsed times, moving "backward" through the various network paths. The predetermined date for the end event might be the date set by management or the date imposed by a customer. The T_L calculated for the first event on the network indicates the latest date the task(s)/project(s) can be started without causing the end event to slip beyond the predetermined target date (see Fig. 5).

After both the earliest expected date (T_E) and the latest allowable date (T_L) have been computed for each of the events, slack may be determined for each path in the network. Slack is the time difference between the earliest expected date and latest allowable date: slack $= T_L - T_E$.

The amount of time the expected date can slip before it equals the latest allowable date (T_L) can also be used as the definition of slack. Slack can be positive, negative, or zero. When the latest allowable date (T_L) is later than the earliest expected date (T_E), positive slack exists. Positive slack is "time-to-spare."

The longest time path or sequence of activities through a network is called the critical path. This path controls the completion date for the task(s)/project(s) represented by the network, since all other paths are shorter. Should the length of time for the critical path be the same as the established completion date for the network, there will be no time-to-spare. This time-to-spare relative to the established completion date is "slack time." In Fig. 5, the slack time for the critical path would be zero. (Note that until a schedule date or directed date is applied to the network end event, the slack value of the critical path is *always necessarily zero*.) Sometimes the length of time for the critical path exceeds the established date for completion. In this case the critical path is said to have negative slack. There is *no* time-to-spare; in fact, a projected time slippage condition beyond the established completion date exists. In like manner, there can be "positive slack" where the duration of the critical path is less than the scheduled time-to-perform from the established start-to-completion dates, indicating that the network activities will be completed with time-to-spare.

Each series path in the network will have a slack value in relation to the established completion date for the project. In this respect each and every series path has a measurable "degree of criticality" which can be positive, zero, or negative. By definition, the longest time path is the most critical in relation to the established completion date and hence is called the critical path. All other paths, which are shorter than the critical path, are therefore called slack paths. Two or more paths may have the same duration and so will have the same slack value. Should these equal paths be the longest in the network, there will be two or more critical paths for the same network.

It should be emphasized that the slack time for a series path pertains to *the entire path* and not to any one event or activity in particular. Any change in the activity time for any one activity in the path series will change the slack value for the entire path.

In Fig. 5, the value of slack is zero for the path through events A, B, and E. Since this is the longest time path through the network, it is the critical path. Other paths through this network have positive slack up to three weeks (A, D, E).

Scheduling

Once the network has been prepared and the time estimates made, the calculations of expected time, latest time, slack, and the critical path reveal whether or not the plans are acceptable. Usually, the plans must be reconsidered owing to the length of time they take and the considerations of the resources (people, equipment, and materials) required. The plan must be converted to a schedule. Scheduling is the conversion of the plan into a set of specific dates that govern the start and completion of work and involves the allocation of resources required to achieve the planned objectives.

Many times, when the initial plan is completed, negative slack will exist. This occurs because, in conforming with the basic rule of first laying out the network without regard for time, the engineer planned the job the way he would like to do it. The scheduling job now involves balancing the work and resources to achieve a schedule which can be met. By first examining the paths with negative slack and by reallocating resources and adjusting activities, the planner can draw up a work plan that is realistically phased with scheduled requirements. The activities with positive slack should be considered second since they provide a latitude for scheduling resources. Once established, the schedule should not be considered changeable at will. It should only be changed when objectives are changed, which essentially means that the plans to achieve these objectives require modification.

Day-to-day control

As the work progresses, there are changes that affect the PERT network: slippages occur, key personnel become unavailable, unexpected breakthroughs are made, activities are accomplished faster than anticipated. This information must be accumulated for analysis, to determine the effect on all interrelated parts of the project, so that the plan can be updated as the schedule demands.

The network can also be used during this phase (or at any time) to assess the effect of contemplated changes on the schedule. This process, called simulation, can provide a quick determination of the impact of a proposed change in the plan.

In engineering, as well as other areas, the network can (by being hung on the wall and information posted on it) serve as a visual reminder of the work to be done, who is to do it, and when it is to be done. As activities are completed, the completion dates should be recorded on the network and the activity checked off. As more information becomes available on the expected time needed to accomplish an activity, the new estimate should be written on the network. This day-to-day use of the network provides the latest information available. On a routine basis, new T_E and T_L calculations can be made and the effect on

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schedule measured. When slippages affect the schedule, an analysis must first be made into the cause and possible solution of the problem. Only then should changes be made in the plans and the schedule adjusted to assure successful completion. If the network is not updated and continuously used as a working tool, PERT becomes merely an extra exercise. The value of the technique lies in its use as a dynamic reflection of the work which must be done. As the project progresses, the network serves another valuable purpose—it can be used as a communications tool. It is a basic reference document which can be used graphically in discussing the project with other engineers and management.

One of its limitations, however, is its use as a visual aid in top management conferences or summary level presentations to the customer, where detailed network information is not required. We have found, more often than not, that the network must be translated onto a time base for presentation (by using a Gantt chart, for example).

Task plan vs. project plan

This article has discussed PERT in terms of the engineer's role, whether he is working on a single task or as a member of a project team. If he is on a project team, the network he prepares is only part of the total project network plan. His network cannot be prepared in a vacuum; it must be prepared with the engineers responsible for other parts of the project. The network system depends upon planning of all interrelationships; interfaces between one engineer and another must be shown. We have found that many times two or more engineers have different conceptions of what they are going to do for each other. The network points out such discrepancies because the plans cannot mesh. Whether or not the engineer prepares the network for part of a larger project or for a task for which he is solely responsible, the basic rules of network preparation are the same.

PERT/COST estimating

Many engineers, as they acquire experience and understanding of the PERT (Time) techniques, ask "Why not include cost estimating?" In June 1962, the government (DOD and NASA) introduced PERT/COST. The principles are relatively simple although the terminology is sometimes confusing. The basic principle of PERT/COST is that the network can be used for both time and cost planning. The work breakdown structure, as previously described, serves as the coupling device with cost estimating done on a "work package" level. Thus the engineer would estimate his costs by time-phased work package.

There are also proponents of other methods, including those who prefer to estimate for each activity. On large programs, involving many labor skills and people, this has been found too cumbersome. In smaller applications it may be possible. In process industries and in the construction industry, where the application of manpower has a linear effect on time, they have been using a cost extension of CPM, where one objective is to optimize cost and time to determine the most applicable schedule and cost for the project. PERT/COST, on the other hand, is simply a discipline for estimating costs and collecting actuals versus the estimate. (To delve into the details of these systems in this limited article is not practical. The interested reader should refer to the publications listed in the bibliography.)

Use of computers

In attempting to convey a basic understanding of the concepts of PERT as it relates to and benefits the engineer, the application of computers in processing PERT has not been discussed. When PERT is applied to large projects, the use of a computer becomes essential in order that the information on a multitude of activities can be processed in a reasonable amount of time. Most computer manufacturers have PERT programs available and many companies and government agencies have prepared their own. In addition, there are programs available for producing networks using plotting or drafting machines tied in with the computer.

It must be remembered that the use of the computer does not vary the technique; the computer is simply the mechanism for rapid processing of a large volume of data. Possibly the emphasis placed on computer usage with PERT has tended to overshadow the advantages to be gained by applying the PERT technique manually and has discouraged its use by engineers in the thought process applied to planning and controlling modest tasks.

Conclusions

In conclusion, it must be restated that PERT is neither a panacea nor solely an automated means for planning. PERT planning must be done competently, with an understanding of both the tool and the project. It can only be done effectively by the engineer or project engineer, however odious planning may seem to him.

When used competently, PERT yields many advantages. It offers a plan which is well developed and is easy to communicate, showing clearly its objectives and interrelationships. It is an improved method of time and cost measurement of tasks, aiding in improved assessment of accomplishment. It is a predictive tool to highlight potential problem areas. It provides the capability of examining alternative plans by simulating changes.

It must be emphasized that proper employment of PERT as an effective working tool necessarily requires a full understanding of the technique and its assimilation by the engineer as part of his normal discipline in the planning and control of assigned tasks or projects.

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Note: This list is abbreviated. The interested reader should refer to the third item for an excellent compendium of references on the subject.

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